NASA TECHNICAL TRANSLATION NASA TT F-14466

PHYSICAL AND TECHNOLOGICAL CONDITIONS OF MODELING ACOUSTICAL FIELDS IN ARCHITECTURAL ACOUSTICS

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(NASA-TT-F-14466) PHYSICAL AND TECHNOLOGICAL CONDITIONS OF MODELING ACOUSTICAL FIELDS IN ARCHITECTURAL ACOUSTICS Z. Kesner (NASA) Feb. 1972 25 p
N72-32658
CSCL 20A G3/23
Unclas
43307

Translation of "Fyzikalni a technieke podminky modelovani akustickych poli v architekturni akustice," Slaboproudy obzor, Vol.31, No. 1, 1970 pp. 18-24

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 FEBRUARY 1972

NASA AM 72-18

Slaboproudy obzor, Vol.31, No. 1, 1970

PHYSICAL AND TECHNOLOGICAL CONDITIONS OF MODELING ACOUSTICAL FIELDS IN ARCHITECTURAL ACOUSTICS

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Abstract

The article deals with the physical and technological agreement conditions between the model and the original acoustic field. The effect of individual factors on the accuracy of the results and on the choice of the model scale is discussed. The main limitation is the frequency dependent absorption of ultrasonic waves propagating in the air; from the point of view of the measuring apparatus, electroacoustical transducers present the most challenging problems. The modeling of absorbing materials can be accomplished with satisfactory accuracy.

1. Introduction

The modeling of complex physical systems for the purpose of an experimental study of the laws which govern their behavior, technology is used in a number of scientific disciplines. As far as results are concerned, it is immaterial which physical principle is used in the model, as long as the behavior of the modeled magnitudes can be described by the same laws as in the case of the original system. The acoustical field in closed space is so complex that during the solution we must resort to experimental methods, and mathematically, we can formulate only a few partial problems. Experimentation in spaces with normal dimensions is difficult, expensive, and time-consuming. Therefore, since the very beginning of acoustical science, attempts were made to solve some problems with the aid of models. Given the technological possibilities which were available at that time, the function of these models was primarily demonstrative.

Three-dimensional acoustical modeling technology is the culmination of the effort to obtain physical agreement between the model and the original. The propagation of sound waves in the model is subject to the same laws as the propagation of sound waves in the original space (with the exception of certain limitations of a physical and technical nature). The results of acoustical measurement processes in the model can then be applied to the original space. We anticipate that the main contribution of modeling technology in archtectural acoustics will be this application. When a new space is proposed, its acoustical characteristics can be verified and optimized on a relatively cheap model. Other methods available to space acoustics are not a sufficiently good guarantee against various acoustical inadequacies, which can only be partially removed after the construction has been finished at considerable cost in each case.

2. General Agreement Conditions for the Model and Original Acoustical Field

The agreement between the physical characteristics of the acoustical field and the model space and the corresponding original is determined by insuring the agreement of boundary conditions on the walls of the space, the agreement of the conditions for the propagation of sound waves, and by the agreement of the characteristics of the source and receiver of the acoustical signal. A more detailed analysis of the individual conditions will show that a perfect model cannot be obtained, both for physical and technological reasons. The model can only be perfected above a certain a bound only at tremendous technological cost. Since the study of the acoustical characteristics of projected spaces on models is only feasible if it results in substantial financial savings, an optimum compromise solution must be found for certain measurement methods the degree of agreement between the modeled space and the original which insures the agreement of the measurement results with an accuracy which is comparable to the accuracy of the corresponding methods which were applied in the original space is sufficient.

The acoustical field in the original space can be formally described by the wave equation

$$\frac{\partial^2 \Phi_o}{\partial x_o^2} + \frac{\partial^2 \Phi_o}{\partial y_o^2} + \frac{\partial^2 \Phi_o}{\partial z_o^2} = \frac{1}{c^2} \cdot \frac{\partial^2 \Phi_o}{\partial t_o^2}. \qquad (1)$$

All boundary conditions $f_o(x_o, y_o, z_o, t_o)$, which determine the solution of the equation take into account the form and absorptivity of the limiting walls, as well as the radiating characteristics of the transmitter, the sound source, and the duration of the excitation signal.

Similarly we can write for the modeled space whose linear dimensions with respect to the original are in the ratio 1:n

$$\frac{\partial^2 \Phi_m}{\partial x_m^2} + \frac{\partial^2 \Phi_m}{\partial y_m^2} + \frac{\partial^2 \Phi_m}{\partial z_m^2} = \frac{1}{c^2} \cdot \frac{\partial^2 \Phi_m}{\partial t_m^2}. \qquad (2)$$

The boundary conditions $f_m(x_m, y_m, z_m, t_m)$ of the model are related to the same conditions in the original by the relations

$$\begin{aligned} x_m &= x_o \cdot \frac{1}{n}, \\ y_m &= y_o \cdot \frac{1}{n}, \qquad t_m = t_o \cdot \frac{1}{n} \cdot \frac{c_o}{c_m}. \qquad (3) \\ z_m &= z_o \cdot \frac{1}{n}. \end{aligned}$$

These relations define, of course, only the shape fidelity of the reduced model and the necessity of maintaining the agreement ratio l/λ as in the original. The relations imply the necessity of a time and frequency transformation of the excitation signal on the model scale. If we transform all frequencies of the excitation signal on the model scale $f_m = f_o \cdot n$, the corresponding wave length $\lambda_m = \lambda_o \cdot \frac{1}{n}$ will be shortened and the agreement ratio l/λ for the original and for the model will insure the same degree of bending phenomena during the propagation and reflection of sound waves.

3. Effect of Absorption during the Propagation of Sound Waves in the Air

When sound energy is transferred in an air medium, the sound wave is damped. The magnitude depends on a number of parameters, above all on the steam content and the frequency of the transferred sound. The acoustical characteristics of concert halls, theaters, etc., are affected by absorption during propagation only at the upper edge of the audible frequency range. Thus, for example, a 4 mV coefficient which takes into account the absorption effect in the equation which is used to calculate the duration of the reverberation is negligible in the range below 5 kHz in comparison to the total absorption of the limiting walls. The reverberation duration is only affected by it in the region above 5 kHz.

The acoustical field modeling conditions imply the necessity of the same absorption ratio on the walls and absorption during propagation, for the model and the original. Hence, the ratio

$$\Sigma \alpha_m S_m : 4 m_m V_m$$

in the expression for the reverberation of the modeled space should agree with the ratio $\Sigma \alpha_o S_o : 4 m_o V_o$.

Because the ratio of the areas is $S_o/S_m = n^2$ a $V_o/V_m = n^3$, , we should have

$$m_{fm} = n \cdot m_{fo}. \quad (4)$$

where m_{fm} is the sound energy damping coefficient for the measured frequency of the model, n is the model scale, m_{fo} is the sound energy damping coefficient for the original frequency. This also follows from the consideration about the shortened wave path in the model versus the original on the scale 1:n. To retain the energy loss ratio during propagation and refraction, the coefficient m should increase n-fold.

3.1. Analysis of Sound Absorption Characteristics

The attenuation of a planer sound wave in zir is defined by equation

$$E(x) = E(0).e^{-mx}, \qquad (5)$$

where $E(x)$ is the intensity at the dixtance x from the point $(x = 0)$, where x is the intensity $E(0)$, m is the sound energy damping coefficient. In the case where the wave plane has a general shape, when the intensity decrease further depends on additional factors, the losses caused by the nature of the propagation and the attenuation in the air are also taken into account, and the constant m has general validity.

The damping of the sound wave energy during propagation in a homogeneous and isotropic air medium is caused by two effects. One of these is the internal friction between the molecules of vibrating air and the heat exchange between the compressed and expanded zones of the medium. Because of this the processes in the sound wave are not exactly adiabatic. This absorption component m is sometimes called "classical," because it has already been studied in detail in the beginning of acoustical science by Kirchhof [1]. For this component the relation

$$m_1 = C(T).f^2, \qquad (6)$$

holds where $C(T)$ is the effect of a number of physical parameters, which are functions of the temperature, f is the frequency of the sound wave.

are

Another reason for the absorption are relaxation processes in diatomic gas molecules which are the main constituents of air. A part of the energy of the vibrating medium is dissipated during the compression in the vibration of the individual atoms which form the molecule. This part which was lost to the sound wave is of course, dissipated. The magnitude of the sound wave damping varies in accordance with the ratio of the period T of the sonic process to the relaxation time τ, which characterizes the velocity of energy transfer. According to Knudsen and Kneser [2] this "molecular" absorption component can be described by the relation

$$m_2 = A(T) \cdot \frac{1}{\omega\tau + \frac{1}{\omega\tau}} \cdot f, \qquad (7)$$

where $A(T)$ is a coefficient which depends on the temperature, τ is the relaxation time for the gas, $\omega = 2\pi f$ is the sound wave angular frequency.

This expression attains a maximum at a frequency for which $\omega = \frac{1}{\tau}$.
It has been determined that in the air it has a considerable effect on the steam content volume. Because of the many influences which determine the molecular absorption values, it is necessary to determine the relationship for the position of the absorption maximum, and therefore also the values of the relaxation period and the air humidity experimentally, also the quantities $C(T)$ and $A(T)$ from the relations (6) and (7).

In addition to the authors [2] a number of additional authors have studied this problem since the early 30's. Winkler [3] tried to summarize the results which were needed for model measurements, and, at the same time, carried out a number of additional measurements.

The relationship between m and the frequency, air humidity, and the additional factors can be expressed approximately by the formula

$$m = m_1 + m_2 = (33 + 0.2t) \, . \, f^2 \, . \, 10^{-12} + \frac{M \, . \, f}{\frac{k}{2\pi f} + \frac{2\pi f}{k}}, \tag{8}$$

where m_1 is the classical absorption component, m_2 is the molecular absorption component, t is the air temperature, f is the frequency, M is a function of temperature, k is the reciprocal of the relaxation period which depends on air humidity.

An idealized relationship between m and the frequency with relative humidity as the parameter is given in Figure 1. For ideally dry air, the value of the coefficient m is given only by the classical absorption component m_1 which is a quadratic function of the frequency. Already for very low humidities, we have in the frequency relationship m a delay. As the humidity increases, this delay moves on to higher frequencies and becomes less pronounced. The maximum molecular absorption for the frequency range 1 to 100 kHz lies in the relative humidity range from 10 to 50%. In this range the frequency relationship is irregular. The region $F > 50\%$ lies to the right from the molecular absorption maximum, almost up to 100 kHz. Therefore the relationship $m = f(F)$ is again a linear function of f^2, and with increasing humidity the absolute value of m decreases. From the standpoint of model measurement two relative humidity regions are important: the low humidity region $(F < 5\%)$ and the usual humidity region $(F > 50\%)$. In both regions the frequency relationship m is almost exactly quadratic, and the absolute values of m are smaller in the low humidity region than in the usual humidity region.

3.2 Influencing Model Absorption Measurements in the Air and Compensation Possibilities

This problem cannot be analyzed generally, the measurement methods which are used must be divided into groups in accordance with the band widths of the measurement signal, the size of the time interval in which we evaluate the response in the space, etc. From all these standpoints the most difficult method is the subjective evaluation of acoustical characteristics through listening to natural signals, which was worked out by Spandock. Even with minimum quality requirements the frequency band 50 Hz to 10 kHz must be transformed into the model, which is more than two decades in which the values of m vary from 4×10^{-6} to 4×10^{-2}.

This band width limits the maximum model scale which can be used, but even for a scale which does not exceed 1:10 it is not possible to have, for higher frequencies, the ratio m:M in the model the same as in the original. If we want to simulate all the parameters of the acoustical field using this model technology, the conditions for the reverberation process in the model must agree with the original. Therefore in the relation for the reverberation period

$$T_o = \frac{0.164 V_o}{\sum \alpha_o S_o + 4 m_{t_o} V_o}, \quad T = \frac{0.164 V}{\sum \alpha_m S_m + 4 m_{t_m} V_m} \quad (9)$$

we must maintain the agreement ratio $\sum \alpha . S : 4 m V$.

In order to see whether this condition is satisfied, we calculate the effect n of the absorptivity of the walls and the equivalent damping in the air

$$\sum \alpha S = 4 M V$$

and obtain a corrected expression for the reverberation time

$$T = \frac{0.16}{4(M + m)}. \quad (10)$$

Hence $(M : m) = 0{,}017$. Figure 1 shows the value $(M+m)$ for the typical reverberation period behavior (2 s for low frequencies with an upward drop). For the model measurements we set the condition $M \cdot m$.

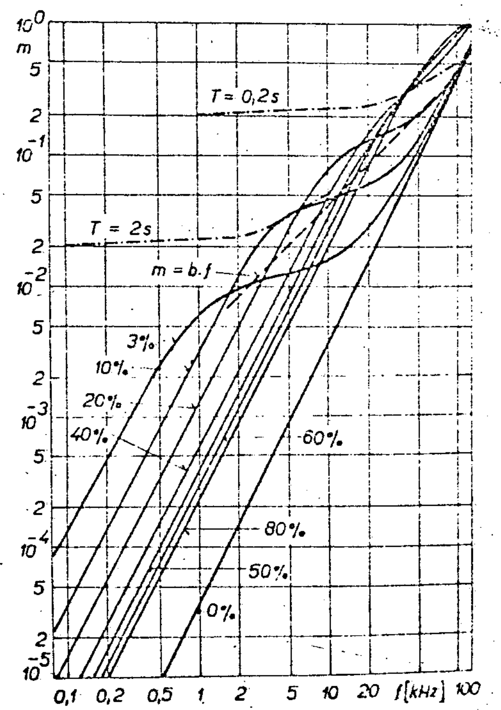


Figure 1. Acoustic absorption coefficient m versus frequency for various relative humidities.

The linearity of m as a function of the frequency follows from the modeling fidelity condition.

Equivalent absorption coefficient M for the reverberation period in the original $T_o = 2$ s and m = 10.

A comparison of the values M for individual frequencies with $m = f(F)$ for 50% relative humidity shows that up to the frequency 5 kHz the ratio is $M : m = 3 : 1$. The same curve for $T_m = 0.2$ s shows that it is not possible to obtain for the model field a similar spacing from the curve $m = f(F)$ which corresponds to the usual humidities. Only for or $F = 100\%$

the spacing is acceptable. It is difficult to retain in the model such ratios, and in both cases the model must be enclosed in a tight casing in which the necessary degree of relative humidity is maintained. For the usual humidities $(60\,\% < F < 80\,\%)$ the equality $M = m$ is attained at $f_m = 20$ kHz. A reduction in the effect of m on the stationary measurement can only be attained through a relative humidity reduction of the air below 3%.

For wide band and pulse measurements the ratios are different. Because we are only investigating a bounded time segment of the pulse response, we cannot compare m with the statistical value of M which was obtained from the reverberation period. When measurements are made in the original band, the effect of damping in the air is negligible (for 5 kHz the damping for 300 ms is 1/2 dB). In the model band because of a faster increase in m with the frequency than that which corresponds to the model fidelity condition $(m_m = n \cdot m_o)$ m attains values which are comparable to the absorptivity of the walls. The disadvantage is, of course, first of all the fact that the individual components of the pulse spectrum are damped during propagation in various degrees (within 1 frequency decade m varies by an order of 2). Therefore, during wide-band measurements the time and frequency absorption relationship in the air must be compensated. The first person to study this problem was Winkler [3].

During narrow-band measurements, taking into account the damping effect during propagation is simpler. Only one value of m which corresponds to the mean frequency of the spectrum need be considered. When the amplitude response configuration is evaluated, the magnitude of the individual responses need not be related to E_o^2, but to $E_o \cdot e^{-mct}$. A similar compensation can also be made by introducing an exponentially increasing gain with an adjustable slope. The undesirable effect of absorption during propagation on the measurement results in the model and original acoustical field can only be removed with the aid of frequency and time-dependent compensation in pulse-excited space. Methods which rely on other types of signals, irrespective of whether the signal is stationary or natural, can only limit the absorption effect through the use of media with low relative humidity (F [illegible] 3 %).

4. Model Space Absorption Wall Characteristics

The surfaces which are used in the model must have such physical characteristics that their behavior with respect to ultrasonic frequencies, whose pitch is given by the transformation of the acoustical field, must be the same as the behavior of normal materials with respect to the original frequencies. Hence both the real and imaginary acoustical impedance components of the model wall space must agree in the model frequency band, as in the case of the original space walls in the acoustical band. Only then the incidence waves will be reflected, as far as the phase amplitude and direction is concerned, as in the real space. To insure that this condition is met is difficult, because from the standpoint of measurement technology the appropriate equipment is no available. Interferromagnetic impedance measurements of acoustic materials is very difficult when the frequencies exceed 5 kHz. Even from the material selection standpoint used for the construction of the model walls we do not expect configurations which will agree, and also in the original frequency band acoustical impedance is usually not used: the acoustical impedance, as a rule, is determined only during the development of absorptive materials.

The statistical acoustic absorptivity coefficient which is determined by the reverberation method gives the ratio of the intensities of the incident and reflected waves without considering phase ratios. Because neither during the design nor during the measurement of absorptive materials the effect of the acoustic wave phase is not taken into account, there is no reason that this be done when equivalent typical acoustical surface models are sought.

The surfaces which occur in the hall can be classified into a number of fundamental groups in accordance with their absorptive characteristics and function: 1) reflecting surfaces, 2) porous materials, 3) perforated panels, 4) vibrating panels, 5) public .

The theoretical relations between the mechanical arrangement and the absorptive properties of the majority of materials have been known for a long time. Agreement between theory and practical results is, of course, limited, which is due to difficulties arising in the determination of material constants and the dispersion in their values. Therefore also in the selection of absorbent materials for the model the experimental approach is the fastest way to the goal when a reverberation chamber is used.

4.1 Minimal Reflective Surfaces Absorption

In the original spaces such surfaces are formed by plaster, smooth concrete surfaces, wooden nonvibrating lining, etc. The absorptivity coefficient of such walls fluctuates in the medium frequency band by approximately 2%. It is not possible to obtain the same values in the model frequency band, because of theoretical reasons. Every hard, smooth stiff wall has a certain absorptivity. This is caused by friction between the vibrating molecules and the energy heat exchange between the wall and the vibrating environment. The magnitude of this minimal absorptivity is a function of the frequency [5]

$$\alpha_{min} = 1.8.10^{-4}\sqrt{f}. \qquad (11)$$

This relationship which is shown in Figure 2 gives the lower boundary for the wall absorptivity which can be obtained in the model. For comparison the curves α for smooth and varnished gypsum plaster are also shown. Sound absorption coefficients for other smooth materials (organic glass, glass, varnished wood) differ very little among themselves and all of these lie near the curve α_{min}

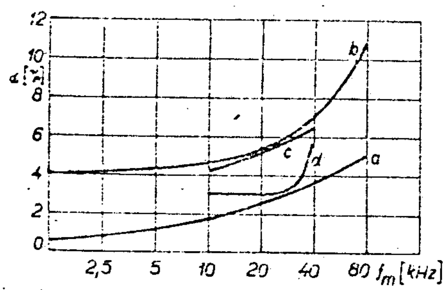


Figure 2. Minimal wall absorption as a function of frequency (curve a), varnished plywood absorption coefficient (curve b), unvarnished gypsum surface absorption coefficient (curve c), and varnished gypsum surface coefficient (curve d).

4.2 Admissible Error in the Simulated Acoustical Absorptivity Coefficient

The reverberation method which is used to determine the statistical acoustic absorptivity coefficient can determine the coefficient only with limited accuracy. Under real conditions the measurement error varies between 5 to 10%. In the model we must expect a further decrease in the accuracy because the reverberation time difference in an empty chamber and the chamber with the model is smaller and additional influences are acting, so that 10% should be considered as a lower bound for the error. Therefore it doesn't make any sense to try to obtain more exact agreement between α_0 and

α_m than 10%. During the pulse excitation of the space the inaccuracy in the simulated acoustic absorptivity coefficient for the individual surfaces will manifest itself through a different amplitude configuration of the pulse response. If the incidence wave has the intensity E_o after the first reflection, E_1 ... can be written as

$$E_n = E_o(1-\alpha)^n. \tag{12}$$

Figure 3 shows the difference of the reflected wave level in dB as a function of the reflecting surface absorptive coefficient. The parameter is the relative error $\frac{\Delta\alpha}{\alpha}$.

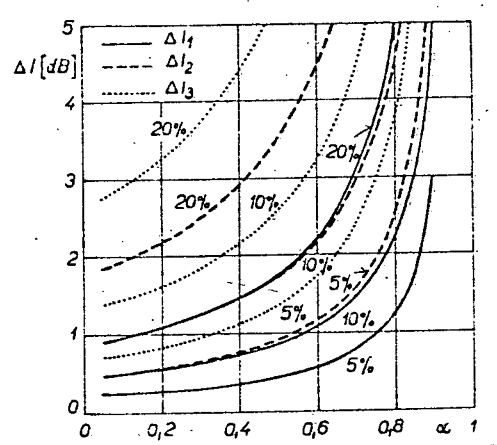


Figure 3. Difference in the intensity of the reflected sound wave for a particular absorptivity coefficient error $\frac{\Delta\alpha}{\alpha}$ (5, 10, 20%) as a function of the absorptivity coefficient and reflection order.

The relationships given above imply that various absolute values of α make no pretense to simulation accuracy. If we require the same error ΔdB in the entire range of α then the admissible absolute error $\Delta\alpha$, is inversely proportional to α. The limiting values of ΔE can be considered to be 2 dB from the standpoint of pulse response fidelity. This value corresponds to the region $\alpha < 25\,\%$, $\Delta\alpha > 35\,\%$, which means that the reflecting surfaces can be modeled approximately with sufficient accuracy. In the region of mean values around 50%, we can allow an error $\Delta\alpha$ around 20% and for $\alpha >$ 75% the admissible error is $\Delta\alpha <$ 10%.

5. Effect of Transmitter and Receiver Direction Characteristics of the Measured Signals

Every acoustical measurement result includes, in addition to the characteristics of the limiting walls which affect the configuration of the acoustical field, also the characteristics of the source and receiver of the measurement signal. The time and frequency curve of the model measurement signal can be obtained from the simple transformations which were given earlier. The decisive factor as far as the accuracy of the model measurements are concerned are first of all the direction characteristics of the transducers used. The direction characteristics are implicitly a part of the result of any method, but the most pronounced differences between the characteristics of modeled and original transducers are evident in the untreated pulse response in the space.

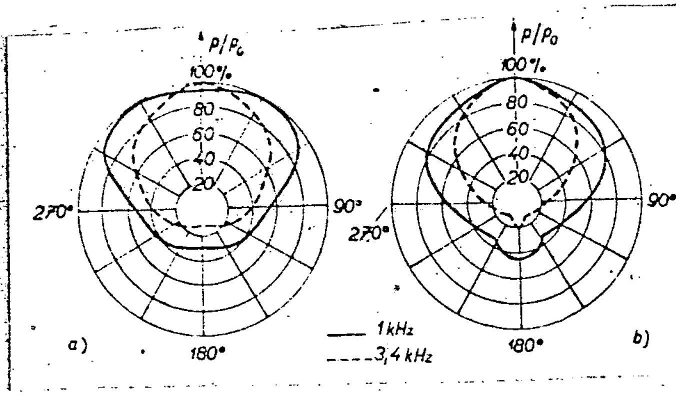
The configuration of the pulse response $r(t)$ of an enclosed space is determined, among other things, by the shape configuration of the limiting walls with respect to the connecting line between the sound source and receiver. We can think of it as the sum of all successive reflections, including the direct sound

$$r(t) = \sum_{k} a_k \delta(t - t_k). \qquad (13)$$

The time configuration of the individual reflections is determined by the corresponding path differences. The amplitude of the individual reflections is determined by the relative level with which the measured pulse was emitted in the appropriate direction and by the relative microphone sensitivity in the direction of incidence, in addition to the shape and absorptive properties of the reflective surfaces (with respect to the direction of direct sound). Hence the agreement of the pulse response in the model and the original depends equally on the shape fidelity of the model, on the agreement of the absorptive properties of the walls, and on the agreement of the direction characteristics of the transmitter and receiver. In measurements of a physical nature we use most often, both on the transmitting and receiving side, a zero order transducer, which has a simply defined spherical characteristic. The accuracy of its maintainance, of course, deteriorates because of the shortened wave length of the emitted signal. Other simple types of directional characteristics, such as for example an eight or cardioid type can be realized exactly even with greater difficulties.

Measurement processes which attempt to include in the results the effect of the emitting and receiving characteristics of sources and receptors of natural signals, utilize an artificial mouth and an artificial ear. Their directional characteristics (Figure 4) can be attained technically by approximating the average characteristics which were determined through the measurement of a number of subjects.

Figure 4. Directional characteristic of human mouth (a) and "artificial ears" (b).



Theoretically the simplest method for obtaining directional characteristics which agree for the model frequencies is the maintainance of a coincident ratio of the transducer dimensions to the wave length. However, this solution is impractical for sound sources from the standpoint of loading capacity, and for microphones from the standpoint of sensitivity and remote noise voltages. The only source whose dimensions are sufficiently small, and has also the characteristics of a zero order source, is the spark gap (Figure 5). This, of course, engables us to emanate a single type of measurement signal--the pressure pulse. Its time behavior is given in Figure 6 and the directional characteristic of the spark gap is given in Figure 7. Special electrodynamic band transducers were developed to radiate other types of signals (Figure 8). However, with these it is not possible to obtain even in the best case axial symmetry of the directional characteristic [6].

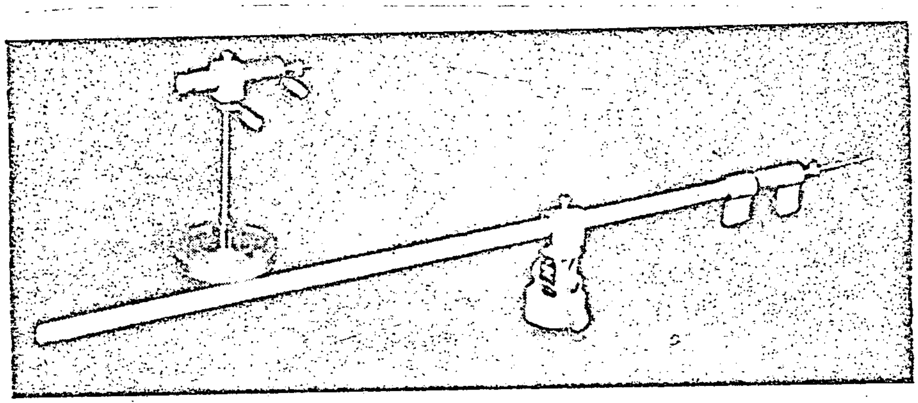


Figure 5. Spark discharge source for model measurement.

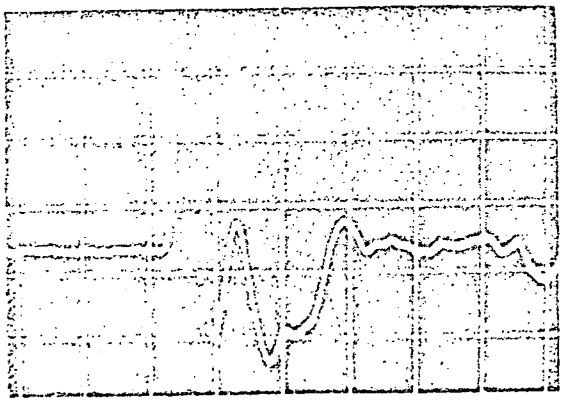


Figure 6. Time behavior of the measurement pulse.

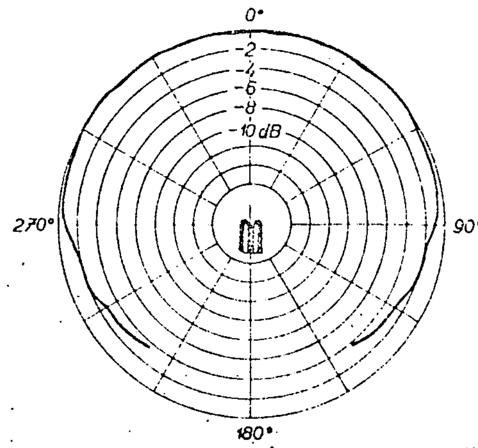


Figure 7. Spark plug directional characteristic.

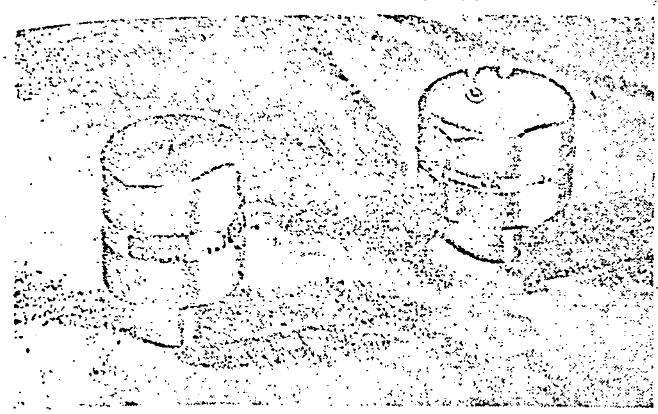


Figure 8. Electrodynamic ribbon loudspeakers for model measurements.

In the case of microphones we can take for the lower dimension bounds the B & K microphone, type 4138, whose diameter is 1/8 of an inch. For this microphone the deviation from the spherical characteristic at a frequency of 40 kHz is 6 dB, which is too much from the standpoint of amplitude fidelity.

The model equivalence of artificial mouths and the artificial ears which are designed in a number of ways [7] imitate the corresponding characteristics with the usual deviations (Figure 9). However, modern research of the hearing mechanisms shows that, for example, the frequency and directional dependence of the human ear is inadequate to describe the processes in the ear during perception in closed space. Therefore a certain amount of caution is necessary in postulating the relations between the results of model measurements and the subjective evaluation of acoustical characteristics. In the present state model processes should be thought of primarily as a physical measurement method.

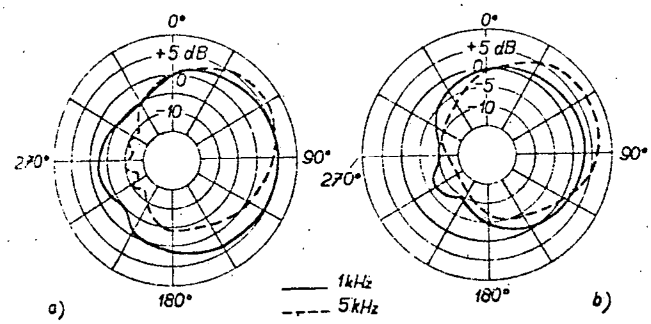


Figure 9. Directional characteristic of the human ear (a) and the artificial model ear (b).

By comparison with the accuracy of the simulated acoustical absorption coefficient the effect of the directional characteristics is the main factor which determines the amplitude fidelity of the pulse response.

6. Optimum Model Scale

The scale on which acoustical models of spaces are made is the result of a compromise between physical technical factors and economic considerations. The frequency band of sound signals which are perceived by the ear in a closed space covers three decades. The individual frequencies are not equally important. First of all, the individual frequencies are not uniformly distributed in the spectrum of natural signals. The spectrum of human speech has the centroid in the neighborhood of 1 kHz, and for music the most important region is the region in which the ranges of the majority of orchestral instruments overlap, i.e., approximately 300 Hz to 2 kHz. Therefore the mean frequency decade from 200 to 2000 Hz must be considered, from the standpoint of the acoustical space solution, as the most important region. In this region also the human ear has its maximum discriminatory capacity. Therefore also in modeling acoustical fields this is the most important band and the ratios for these band in the model must correspond to the original with the greatest accuracy.

Absorption during propagation in the air limits the maximum scale which can be used. Because the coefficient m is a quadratic function of the frequency, it is difficult to fulfill the condition that the absorption during propagation be smaller on the upper edge of the frequency band than the absorption on the walls. This restricts the model scale to the highest frequency which we want to study in the model. Every widening of the band by 1 octave requires a corresponding reduction in the model scale. Another limiting factor in the choice of the model scale are electroacoustical transducers, which are technically the most demanding among all the apparatus. Because their frequency and directional characteristics cannot be adapted to the model scale, the deviations from the ideal curves increase with an increasing scale, and the upper limiting frequency which can be modeled decreases.

Economic criteria are applied first of all in modern technological applications to assess the acoustical characteristics of halls which have not yet been built. The total expense for model measurements should not exceed a certain percentage of the cost of the project documentation. The cost of the model itself will depend on its size and therefore also on the selected model scale. It can be assumed that the cost of the model whose dimensions are twice as large will aprroximately quadruple if we take into account labor, material used, etc. Figure 10 shows the frequency with which individual model scales are used in various acoustical laboratories [4].

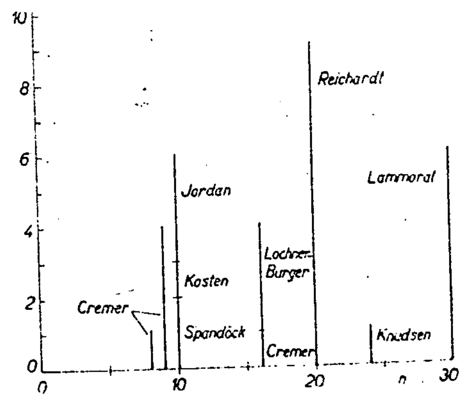


Figure 10. Frequency of model scales used.

We must, of course, be aware of the different requirements as far as the fidelity of the model is concerned. When we study and verify physical laws in a narrow frequency band, we can obtain reliable results even if the scale is greater than 1:20, on the other hand if we transform wide-band natural signals into the model and subsequently evaluate these subjectively, even the scale 1:10 may be inadequate, especially with respect to electro-acoustical transducers.

It follows from the analysis of all factors that the model scale 1:10 is an acceptable compromise between economic and space criteria on one hand and physical and technical limitations on the other hand. We will adopt this scale as the starting point for our concept of model measurement methods [8].

7. Conclusion

The analysis of individual limiting factors shows that the agreement between the model and original acoustical field cannot be perfect. Therefore, the model processes cannot be thought of as a universal method to be used in the experimental solution of acoustical problems. The increasing demands on the accuracy of model measurements have led to a step-by-step study of the individual factors which determine the fidelity of the model acoustical field. The region in which sufficient agreement is obtained, is sufficiently wide, given the present state of electroacoustical equipment, and if the limiting factors are taken into account, a variety of space acoustic problems can be successfully solved with the aid of models. In addition to architectural acoustics where models can be used to optimize the shape of the projected spaces, a number of physical acoustics problems can be solved, such as, for example, the reflection of nonstationary absorptive material responses, the research of scattered reflected structures, etc. Further development depends on perfected electroacoustical apparatus and on the development of measurement technology and space acoustical criteria.

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